THE EFFECT OF DIFFERENT HEAT TREATMENTS

ON THE MECHANICAL PROPERTIES OF STEEL VARYING IN

CARBON CONTENT

by

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I N T R O D U C T I O N

THE EFFECT OF DIFFERENT HEAT TREATMENTS ON THE MECHANICAL PROPERTIES OF STEEL VARYING IN CARBON CONTENT

INTRODUCTION

What is known of the effect of heat treatment on the mechanical properties of steel is very limited as compared with many other subjects of engineering interest. One might say that heat treatment processes are really in their infancy as far as an abundance of knowledge on the subject is concerned. However more is being done today along this line than at any previous time due to the demands made by war conditions.

The object of the tests for this thesis was to obtain data that would give a fairly comprehensive idea of the effect of different heat treatments on the mechanical properties of steel varying in carbon content. It may be well before going any further to consider some of the theoretical effects of heat treatment on steel.

ANNEALING

First we shall consider the process of annealing steel. The annealing of steel may be performed for two reasons, first, to decrease the hardness of the steel in order that it may be more easily machined or mechanically worked in some other way, and second, "to secure a desirable combination of high strength and elastic limit with fair ductility that it may successfully stand the strains to which it is subjected."

The annealing process may be divided into three steps. First, the heating of the steel; second, maintaining it at a constant annealing temperature; and third, cooling it slowly from this temperature to room temperature.

In heating the steel for the annealing process it is necessary to get its temperature up above the critical range because in doing so the structure, even though coarse, is obliterated, and, for the time being, the metal assumes a nearly amorphous structure.

The committee on Heat Treatment of the American Society of Testing Materials recommended the following ranges of temperatures for annealing processes.

Range of Carbon Content	Range of Annealing Temperature
Less than 0.12%	875 to 925 deg. C
0.12 to 0.25 %	840 to 870 deg. C
0.30 to 0.49 %	815 to 840 deg. C
0.50 to 1.00 %	790 to 815 deg. C

The structural change produced by annealing at these temperatures is due to the passage of the steel from that of a homogeneous solid solution to an aggregate of ferrite and cementite. Should the temperature of the steel remain below its critical range a complete structural change would not take place and the annealing would be less effective.

When the steel is raised to the annealing temperature it should be held at this temperature long enough to assure a uniform heating of the piece throughout. The A. S. T. M. recommends an exposure of one hour for pieces twelve inches thick. Larger pieces require a longer exposure.

To obtain the desired results it is necessary to cool the steel slowly from the above temperatures to the temperature of the room. This rate of cooling, of course, depends upon the properties that are desired in the steel. If it is desired to obtain a very soft and ductile steel at the expense of some strength, then the piece should be cooled slowly. If such

a high degree of softness is not desired and a greater strength is the object, then the rate of cooling may be accelerated to meet the demands.

The lower the carbon content the more rapidly may the steel be cooled without affecting the ductility appreciably. Large objects cool more slowly than smaller ones so that it may be sufficient to allow these to cool in air, while those of smaller cross section should have their rate of cooling considerably retarded by allowing them to cool in a furnace under reduced heat.

Sauveur draws the following conclusions regarding the annealing of steel. He states that "(1) in annealing for softness and ductility steel should be heated slightly above its critical range and cooled slowly, as for instance with the furnace in which it was heated, or for greater strength in air, (2) in annealing for strength and high elastic limit combined with fair ductility as well as for resistance to wear, to shock, and to fatigue, steel should be heated to slightly above its critical range followed by cooling in water, or in oil according to the carbon content and requirements and reheated to some 500 to 650 deg. C. in accordance with the physical properties desired, the lower temperature yielding the greater strength but the less ductility."

HARDENING

Hardening consists in raising the temperature of the steel above its thermal critical range and cooling suddenly or quenching in water, oil, or other quenching media which absorbs heat rapidly. Quenching steel has the effect of increasing its hardness more especially as the carbon content increases. It also raises the elastic limit and tensil strength and reduces the ductility. It induces cooling strains and the metal is apt to be very brittle especially for steel of carbon content 0.50 per cent and above. To possess hardening power the steel must be in a condition of a solid solution

since the aggregate of ferrite and cementite formed on slow cooling thru the critical range can not be hardened by sudden cooling.

Sauveur recommends that the quenching temperature should be some 20 to 50 deg. C. above the Ac_1 point in hardening. In heating the steel for hardening the temperature should be raised slowly enough to permit the steel to attain a uniform temperature throughout and should not be too sudden. In commercial practice, however, steel is put directly into a red hot furnace.

As should naturally be expected, the structure of hardened steel is totally different from that which has not been hardened. Before hardening the steel consisted of an aggregate of ferrite and cementite which, upon being heated thru its critical range, was converted into a solid solution (austenite) of carbon or carbide in gamma iron. This was necessary to impart the hardening power. If the metal had been allowed to cool slowly from this temperature thru its critical range it would have returned to its previous condition of ferrite and cementite. If instead, it was cooled suddenly, the time necessary for its transformation would have been too short. In the commercial hardening of steel the cooling is not sudden enough to prevent at least a partial transformation of the austenite, not into ferrite and cementite, but into a more or less transitory form, marking the first step of that transformation and called "martensite." Very frequently the rate of cooling is not sufficiently rapid to prevent the martensite from further partial transformation into a second transition constituent known as "troosite." Martensite and troosite, then, are the ordinary constituents of commercially hardened steel.

TEMPERING OF HARDENED STEEL

Tempering consists of reheating hardened steel to a temperature below

its critical range for the purpose of restoring partially its ductility and softness. Tempering effects are first noticed at about 100 deg. C. and increase in intensity to about 600 deg. C. where the steel once more assumes the characteristics of the normal untreated steel. Therefore the use to which the steel is to be put governs the tempering temperature. According to Sauveur, "If it is desired to retain the greatest possible hardness, necessarily with its accompanying brittleness, the steel should be reheated but slightly above 200 deg. C. as, for instance, in tempering razor blades where extreme hardness is essential and brittleness relatively immaterial. If on the contrary, considerable toughness is indespensible, at the necessary sacrifice of some hardness the steel should be tempered to some 300 deg. C. or even to a higher temperature. The great majority of tools are tempered between 200 and 300 deg. C."

The length of time the steels are held at the required temperature has some effect on their hardness and should be taken into account in the tempering operations. Mathews tempered three hardened pieces of the same steel in a salt bath at 422 deg. C. keeping them at that temperature respectively for 8, 20, and 40 minutes and obtained Brinell hardness numbers of 425, 390, and 340 respectively.

After the desired tempering has been accomplished and it is desired to cool the steel, the rate at which this steel is cooled has little or no effect on the results. In practice the piece is usually quenched for convenience.

The theories for the effect of tempering of steel are a bit complicated but it is enough to state that hardened steel is generally considered to be in an unstable condition and, therefore, tends to return to a more

stable form and actually undergoes this change whenever given an opportunity, when its temperature is raised. At atmospheric conditions the passage of an unstable martensitic condition into a more stable troositic or sorbitic is prevented by the rigidity of the metal. When the metal is heated slightly the rigidity disappears and the transformation takes place. The disappearance of this rigidity increases as the temperature is increased and the greater is the tempering effect. Tempering is nothing more or less than the passing of an unstable state to a more stable state.

M E T H O D

METHOD

APPARATUS

The Thermocouples

Two very important pieces of apparatus used in these experiments were the thermocouples. All temperatures above 300 deg. C. were measured by iron-advance thermocouples manufactured by the Leeds and Northrup Company.

These couples were calibrated against a platinum vs pt-10% rhodium couple as a standard. First it was necessary to calibrate this platinum couple.

The equation for this couple which coincides within 2 deg. C. with the graph of the e.m.f. temperature relation as determined by comparison with the gas thermometer is given as:

$$\text{Log } e = n\text{Log } t + \text{Log } m$$

Here e is in microvolts or millivolts, t is in deg. C., n and m are constants. The equation does not apply below 250 deg. C. because below this point the equation does not fit the gas thermometer comparison.

From the equation it is seen that, in order to calibrate the thermocouple, it is necessary to determine only two points on the curve and thus establish the constants n and m. The two points taken were the melting point of zinc and the melting point of copper, 419 deg. C. and 1083 deg. C. respectively.

To determine these points the zinc was melted in a crucible furnace and the copper in a resistor furnace. When the metal was melted the couple was placed in a fused quartz tube surrounded by a graphite one and inserted

into the molten metal. The metal was then allowed to cool and readings of millivolts on a potentiometer and time were taken. Thus the data for the cooling curve was obtained. A decided break in the curve is the melting point desired. This is the point where the temperature remains constant. From these millivolt readings and the known temperatures for them the constants of the equation may be obtained and a curve plotted which will enable one to determine the temperature for any e.m.f. developed by the couple.

With this standard couple the base metal couples were calibrated. This was accomplished by inserting them both into a tube furnace and raising them both to the same temperature. The temperature can be read directly from the calibration curve of the standard couple and the e.m.f. of the base couple corresponding can be plotted against this value. This calibration is a straight line and can be readily drawn after several points on it have been obtained, as explained above.

Potentiometers were used to read the millivolts developed by the couples. These instruments are more accurate than millivoltmeters because they eliminate any error due to stray e.m.f.s, resistance of the leads, etc.

THE FURNACES

To heat the steel to the higher temperature two alundum tube furnaces wound with nichrome wire were used. Both tubes were 24 inches long, one tube being 2 inches in diameter and the other about 2 1/2 inches. These furnaces were mounted on stools in a vertical position with the bottom of the furnace about 2 1/2 feet above the floor. The bottom ends of the furnaces were fitted with pipe plugs and the upper ends were plugged with asbestos to prevent oxidation of the steel.

THE TESTING MACHINES

The tensile tests were made in a Riehle 100,000-pound testing machine.

In these a Lewis Hayes extensometer was used to determine the yield point. This little instrument has a gage length of 2 inches and is clamped directly to the test piece. Before the yield point is reached the indicator on the dial revolves 3 divisions for every 1000 pounds load registered on the beam of the testing machine. As soon as the yield point is reached, the indicator starts to revolve quite rapidly. This is a very accurate indication of the elastic limit of the steel being tested.

The repeated stress tests were made in a Kommer's Repeated Stress Machine. This machine was set to give the specimens a 3/8 inch deflection in either direction.

The impact tests were made on a Russel Impact Machine. This machine was set for a gage length of three inches.

MATERIAL

THE STEEL

The steels used were all 1/2-inch round specimens which have a composition as rolled of .14, .33, .52, .68, .80 to .90, and 1.10 to 1.20 percent carbon respectively. (Mill analyses.)

The tensile specimens were 10 inches long.

The repeated stress specimens were 9 inches long and turned down to a few thousands over 3/8 inches in diameter before heat treating then ground to size afterward.

The impact specimens were 5 inches long. After they had been heat

treated they were notched in the center with a 3/64 inch milling cutter to a depth that would leave .23 inches of metal on the full side of the specimen.

THE QUENCHING MEDIUM

From a thesis by J. M. Gillet, '15, in which he investigated the effect of different water quenching mediums on the time rate of cooling of steel, the following observations were taken:

(1) The rate of cooling of steel in hot water was materially increased over that in cold.

(2) The results show that caustic lime and strong common salt solutions possess the greatest cooling power of any of the liquids tried, followed by dilute sulphuric acid solutions, and then by alcohol.

(3) Water appears to have the lowest cooling power.

The following considerations were obtained from Bullen:

Pure water has a fairly constant quenching rate up to a temperature of 100 deg. F. where it begins to fall. At 125 deg. F. the slope is very marked. Brine solutions have both a quicker rate of cooling and are more effective at higher temperatures than water. The temperature-time curve does not begin to fall off seriously until a temperature in the neighborhood of 150 deg. F. is reached.

Bullens recommends oil quenching wherever it may be used.

Water quenching increases the internal strain, but for low carbon steels and simple sections of higher carbon steels water may be used.

In these experiments water was used for all the steels except the .90 and 1.20% carbons. This water was changed after every quenching and its temperature thus maintained at about 8 deg. C.

For these two high carbon steels Houghton's Quenching and Tempering oil was used. This oil is extracted from the wool of sheep. The principle

features of this oil are, first, that it is free from oxygen and all ingredients possessing a tendency to oxidize or decompose, second, that it will produce uniform hardness, that it withdraws the heat reasonably fast from the steel, giving it a maximum toughness and hardness, and is easily removed from the work, third, it is absolutely free from moisture, and lastly it retains practically the same speed at temperatures varying from 50 to 250 degrees Fahr.

This oil was also used to temper the steels at 200 deg. C.

To temper the steels at 300, and 400 deg. C. linotype metal was used which started to melt at about 280 deg. C.

GENERAL OPERATIONS

QUENCHING

The steels were quenched from temperatures which were 50 deg. C. above the $A_1 - A_{1-2} - A_{1-2-3}$ line in the Iron-Carbon diagram as given in Sauveur.

Each specimen was grooved at the top to enable a sling of wire to be firmly attached to it. Common stove pipe wire was attached to this sling by which each specimen was suspended in the furnace. One furnace accomodated five specimens while the other could hold about seven or eight. The specimens were suspended at the center of each furnace and the thermocouple placed in the center of each furnace. The plug which was inserted in the bottom of the furnaces was filled with resin which, when it volatilized assisted in preventing the oxidation of the steel. The top of the furnace was plugged tight with asbestos.

The current to the furnace was varied by an impedance coil connected

in series with the furnace winding. The large furnace took a maximum current of 30 amperes A. C. while the other took 12 amperes.

When the desired temperature had been reached it was held constant for about five minutes, then the bottom of the furnace was opened and the wires holding the specimens cut allowing them to drop into the quenching medium in a vertical position.

The advantage of this means of quenching them is that they have little or no chance to cool before they strike the oil or water, as it may be. The vertical quenching gives a uniform cooling to the specimen and eliminates possibilities of warping.

When water was used to quench with it was changed after every quenching. When oil was used the container was placed in a larger bucket and water circulated around the oil bucket to assist in keeping the oil as cool as possible.

ANNEALING

In the annealing process the steels were suspended in the furnaces as before and their temperature raised to the values prescribed by the A. S. T. M. They were maintained at this temperature long enough to allow a uniform heating of all the specimens and then allowed to cool slowly in the furnace by gradually decreasing the current thru the winding.

TEMPERING

To draw the steels at 200 deg. C. the oil bath was used. The oil was placed in a cast iron container in the bottom of which shims were provided to keep the steel off the bottom of the kettle. This kettle was heated with two Meker burners and the temperature of the oil read with a mercury thermometer. After the steel in the bath had reached the desired temperature it was maintained at this temperature for a period of fifteen minutes, as was done in all the other tempering operations.

An attempt was made to use this oil bath to draw the specimens at 300 deg. C. but had to be abandoned due to the fact that the flash point of the oil was reached at just this point and the bath started to burn.

For temperatures of 300 and 400 deg. C. the linotype metal bath was used. This metal melted at about 280 deg. C. To obtain the desired temperature four Meker burners were necessary. It was impossible with the heating facilities at hand to obtain a temperature of 600 deg. C. with this lead bath. Because of this the electric furnace had to be used.

In using both the oil and lead baths an iron red was provided to agitate the bath and thus maintain a constant temperature in all parts of it.

R E S U L T S

A N D

C O N C L U S I O N S

RESULTS AND CONCLUSIONS

DISCUSSION OF CURVES

Per Cent Reduction of Area

These curves were plotted from the average results of the tensil tests. Generally speaking we see an approach to the normal curve by the curves for the annealed, tempered at 400 and 600 deg. C. specimens. The 300 deg. curve drops below these and the 200 deg. below the 300. The hardened curve is the lowest, showing that the ductility of the steels is increased the greater the amount of hardness that is drawn from them.

Now we shall consider these curves more in detail. One peculiar feature about the curve for the normal specimens is that it shows a decrease in ductility in the steel as the carbon content is increased up to .68 carbon and an increase after that to the high carbon steels. This is also the case for the annealed and 600 deg. treatments. There is a continual drop for the 400 deg. treatment, but for the 300 deg. curve this rise comes at the .90 point carbon mark. This affect was not shown in the harder steels because they were not taken above .68 carbon although at this point a drop in ductility is seen. These determinations for the hardened treatment are a bit obscure due to the great hardness of the specimens.

It is hard to find an explanation for this point for it might result from several causes. We might draw our conclusions from the following observations. This .68 steel is a hypo-eutectoid steel in the alpha region which when allowed to cool below the critical range, as the annealed and normal specimens, contains quite a bit of pearlite and some ferrite. The higher carbons contain no ferrite but some cementite. The .90 carbon is

a eutectoid steel containing only pearlite. It may be the effect of this small percentage of ferrite that causes this decrease in the ductility.

For the lower carbons, .14% and .33% carbon annealing seems to reduce the ductility slightly. For the .52% carbon the ductility is increased while at the .68 % carbon the ductility is as normal. For the higher carbons the ductility is considerably less. From these results we see that annealing produces the greatest ductility on steels varying in carbon content from .33% to .68%.

For hardened steel the ductility is greatly decreased and this decrease is more evident for the higher carbon steels.

When the steels are drawn at 200 deg. the ductility is, of course, increased slightly. Steels of carbon content less than .80% drawn at 400 deg. seem to have greater ductility than the normal steels and less for those of higher carbon content.

The 300 deg. curve is lower than the normal and higher than the 200 deg. one as should be expected.

The per cent reduction in area determinations are not as good criterions of ductility as the per cent elongation determinations for the simple reason that the reduced cross section can not be as readily measured as the elongation of the specimen. We shall now consider the results obtained for the per cent elongation curves.

<u>Per Cent Elongation In 2 Inches</u>

Here we see a very decided approach to the normal by the annealed

and 600 deg. curves, especially up to .68% carbon. After this the annealed curve drops considerably below the normal while the 600 deg. curve continues near the normal curve to .90% carbon where it drops below. This shows that there is a very slight decrease in the per cent elongation and thus the ductility for annealed specimens and specimens drawn at 600 deg. C. below the normal up to .68% carbon. Above this the ductility decreases.

One peculiar thing about this is that one would expect a considerable increase in ductility in the annealed specimens over the normal specimens. I can only account for this from the fact that the steels might have been cooled too rapidly in the furnace although every means was taken to prevent this.

The other four curves follow results as should be expected. The 400 deg. curve dropping below the 600 deg., the 300 deg. below that, and the 200 deg. and hardened curves being still lower, the curve for the hardened specimens being the lowest, in fact showing zero per cent elongation at .68 carbon.

In these curves we see the same drop at .68% carbon as was observed in the reduction in area determinations. Another explanation for this and perhaps more correct than was previously offered is the fact that these steels were quenched in water. No cracks due to hardening strains were noticed in the fractures in these tensile test specimens but such cracks were noticed in the repeated stress specimens. This showed that hardening strains had been set up in these steels due to quenching them in water, and that they should have been quenched in oil. These hardening strains undoubtedly acted to decrease the ductility of the steel.

In general then we can state that annealed steels should theoret-

ically exceed the ductility of normal steels except for the higher carbons, that treatment at 600 deg. C. brings the steel very nearly back to normal ductility, this fact being most evident up to the eutectoid point, .90% carbon. The hardened specimens are very low in ductility, but as the temperature at which they are drawn is increased the per cent elongation, and thus the ductility, increases accordingly.

Yield Point

These curves give very good ideas of the effect of heat treatment on the steels. The curves for the hardened specimens and for the specimens drawn at 200 deg. may just as well be disregarded as it was very difficult to obtain a definite yield point on these specimens.

As would be expected the annealed specimens show a smaller yield point than the normal specimens up to .80% carbon, above this the yield seems to be nearly as high as that for the specimens drawn at 300 and 400 deg.

Again we see the approach to the normal of the 600 deg. curve, especially up to .90% carbon. Above this the yield is increased.

There seems to be some discrepency between the 300 deg. and the 400 deg. curve. The treatment at 300 deg. gives a smaller yield point than at 400 deg. for any steel. This apparently disagrees with the general theory that the more hardness that is drawn from the steel the less will be the yield point. Assuming this to be true our only explanation for this error is that there was a mistake in properly numbering the specimens for the two heat treatments.

On the other hand this may be a phenomenon of steels above .52% carbon. The 400 deg. treatment may just modify the austenitic and martensitic structure to cause a greater tenacity of the crystals and thus cause

an increase in the yield point.

In general we can say that the yield point of hardened steels is considerably higher than that for normal steels and that as this hardness is drawn the yield gradually approaches the conditions of the normal steel as rolled. The annealing process tends to still further reduce the yield below that of normal for steels up to .68% carbon, above which the yield increases.

Ultimate Strength

In these curves we see, as in the curves for the yield point, that the annealed specimens drop below the normal ones in ultimate strengths for steels up to .90% carbon, above which their ultimate is increased.

The approach of the 600 deg. curve to the normal is evident here but not as much so as in the other properties of the steel. These specimens show slightly less ultimate strength than the normal specimens up to .90% carbon above which their ultimate is higher.

The same condition exists between the 400 and 300 deg. curves as did for the yield point. That is, the treatment at 400 deg. seems to give greater ultimate strength than that at 300 deg. The same explanations hold as in the yield point determinations. However it might be added that a further proof that the 300 deg. curve should drop below the 400 deg. curve is that the ultimate strength of the hardened specimen is less than the specimen drawn at 300 deg. C. for the .68% carbon.

The ultimate strength of the hardened specimens seems to greatly exceed the other treatments as would be expected. Some difficulty was experienced in pulling these specimens as they persisted in slipping in the grips.

Tempering the specimens at 200 deg. decreased the ultimate slightly below that of the hardened steels. This treatment has the greatest effect on the lower carbon steels and for this reason none of the higher carbon steels were treated in this way.

Generally speaking the ultimate strength of steel of varying carbon content is greatly increased by hardening it. This ultimate strength gradually decreases as the hardness is drawn from the metal by heating to the various temperatures, until it finally nears its original condition when drawn at 600 deg. C. and drops below its normal strength when annealed.

Repeated Stress - Cycles to Rupture

The cycles to rupture plotted for these curves are very good criterions of the ability of steel to resist repeated stresses. Abundant data along this line is more or less deficient so these curves are particularly interesting.

The only treatment which produces greater resistance to repeated stresses than the normal steel is the annealing treatment of the low carbon steels up to .52% carbon. Beyond these steels annealing produces a less resistance to repeated stress. Here we see that treatment at 600 deg. C. does not produce the same effect as it did on the other properties of the steel, that is, it did not approach the normal specimens but rather drop considerably below them. Nevertheless it is seen to follow the general direction of the normal curve.

Treatment at 400 and 300 deg. C. did not produce much variation in this property of the steel from the results at 600 deg.

As was expected, the hardened specimens offered the least resistence to repeated stress while drawing at 200 deg. had very little effect on the

.14 and .33 carbon steels.

The results of these tests are bases for choice of steel and heat treatment for making locomotive rods, crusher jaws, automobile axles, and any machine parts which are subject to reversal of stress.

One thing was particularly noticeable in these tests which was not observed in any of the other tests and that was the effect of water quenching on the .68% carbon steel. Nearly every specimen showed considerable cracking due to the severe strains set up in hardening. This fact shows that steel much above .55 or .60% carbon should not be quenched in water, but should be quenched in oil.

Impact Tests - Energy of Rupture.

The energy of rupture as obtained from the results of the impact tests is a measure of the toughness of a steel.

The plotted results of this test are very interesting. Above .52% carbon we see that normal steel as it comes from the rolls is the toughest. Above this percentage of carbon content the steels drawn at 600, 400, and 300 deg. C. are tougher than the normal, their respective toughness as being in the order just stated.

Annealing apparently does not toughen steel but rather decreases its toughness up to .68% carbon and does not change it materially above this amount of carbon.

The .52%carbon steel drawn at 300 deg., the steels hardened and those drawn at 200 deg. have a relatively low toughness. The two tempering processes vary but little from the hardened specimens.

The toughness of the steels for every heat treatment decreases rapidly to about .80% carbon. The higher carbon steels showed relatively little change

in the toughness for the different heat treatments. This shows that the tougher the steels when normal the greater the effect of heat treatment on that toughness.

General Observations

From the above considerations we may make a few brief summaries of the interesting points that were brought out in these tests.

First in regard to the annealed specimens. They all show less strength than normal steel below .90% carbon and an increase above that point. The ductility of the steel is always less for this heat treatment on steels above .90% carbon, the yield point and ultimate strength are always greater for steels of the higher carbon content.

The steels treated at 600 deg. C. have properties that tend to approach the normal properties of the steel.

The .90% carbon steel is at the eutectoid point below which in the iron-carbon diagram we have austenite above the critical range with pearlite and ferrite below the critical range. For steels above this eutectoid point we have cementite above the critical range with cementite and pearlite below the critical range. At this eutectoid point all of the physical properties showed a transition or reversal for the normal and annealed specimens and those drawn at 600°C, which phenomenon may be accounted for by the difference in the constituents of the steel below and above this eutectoid point.

Many of the points investigated were not new but the results afford a very good reference for the effect of these various heat treatments on the mechanical properties of steel varying in carbon content. By reference to the curves giving the effect on the ductility, strength, resistance to repeated stresses, and toughness, the heat treatment for a given steel for any desired results may be chosen.

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D A T A

C U R V E S

A N D

R E S U L T S

TENSILE TEST

STEEL NORMAL - AS ROLLED

% Carbon	.14	.33	.52	.68	.80-.90	1.10-1.20
Mark or number	A1&2	B1&2	C1&2	D1&2	E1&2	F1&2
Dimensions of	.505	.497	.497	.498	.510	.516
cross section	.502	.497	.494	.492	.510	.516
Load at yield	7490	8275	10380	10990	8478	8170
point	8000	8550	10375	10895		8745
Load at	10810	13355	16510	20880	15330	15850
ultimate	11060	13550	16500	20875	16760	15830
Elongation in	2.96	2.74	2.62	2.38	2.64	2.65
2 inches	2.90	2.73	2.60	2.46	2.66	2.65
Dimensions of	.296	.324	.339	.431	.382	.358
red. cross sec.	.296	.328	.405	.399	.356	.353
Area of cross	.2003	.1940	.1940	.1948	.2043	.2091
section	.1979	.1940	.1917	.1901	.2093	.2091
Area of reduced	.06881	.0825	.0903	.1459	.1152	.1007
cross sec.	.06881	.0845	.1288	.1250	.0995	.0979
Per Cent reductin	65.5	57.4	53.3	25.1	43.6	51.8
of area	65.2	56.4	32.8	34.2	51.1	53.2
Per cent elonga-	48	37	31	19	32	32.5
tion in 2 in.	45	36.5	30	23	33	32.5
Unit stress at	37320	42700	53500	56300	41400	39100
yield point #/sq.in.	40400	44100	54200	57200		41800
Unit stress at ul-	53800	68700	85100	107200	75000	75700
timate #/sq.in.	55850	69800	86000	109800	81800	75700
Character of	Half	Ragged	Ragged	Ragged	Perfect	Fringed
fracture	C.&C.			But Flat	C.&C.	But Flat

REMARKS: C_2 Broke on prick punch mark.

TENSILE TEST

STEEL ANNEALED

% Carbon	.14	.33	.52	.68	.80-.90	1.10-1.20
Mark or number	A3&4	B3&4	C3&4	D3&4	E3&4	F3&4
Dimensions of	.506	.507	.500	.502	.510	.517
cross section	.506		.503	.502	.518	.516
Load at yield	5780	5690		7000	11250	13520
point	5095		8680	6880	14890	15495
Load at ultimate	9270	10850		15940	19300	18420
	9088		13265	15740	20050	20700
Elongation in	2.98	2.77		2.45	2.25	2.40
2 inches	2.85		2.56	2.44	2.35	2.45
Dimensions of	.284	.337		.434	.427	.397
red. cross sec.	.385		.320	.420	.445	.411
Area of cross	.2011	.2019	.1963	.1979	.2043	.2099
section	.2011		.1987	.1979	.2107	.2091
Area of reduced	.0634	.0892		.1479	.1432	.1238
cross sec.	.1164		.0804	.1385	.1555	.1327
Per cent reduction	68.3	55.8		25.3	29.9	41.0
of area	42.2		59.6	30.0	26.2	36.6
Per cent elongation	49	35.7		22.5	12.5	20
in 2 in.	42.5		28	22.0	17.5	22.5
Unit stress at	28750	28700		36400	54800	64500
yield point	25320		43700	34800	70600	74000
Unit stress at	46100	53700		80500	94200	87700
ultimate	45200		66700	79600	95200	99200
Character of	Half	Ragged	Ragged	Ragged	Flat	Flat
fracture	C.&C.					

REMARKS: E_3 Broke in grips. Pulled again and second value taken.

F_3 " " "

D_4 " " "

TENSILE TEST

STEEL - DRAWN AT 200°C (5&6) AT 400°C (7&8)

% Carbon	.14	.33	.52	.68	.80-.90	1.10-1.20
Mark or number	A5&6	B5&6	C7&8	D7&8	E7&8	F7&8
Dimensions of	.508	.496	.496	.498	.506	.518
cross section	.495	.503	.495	.495	.511	.516
Load at yield	11940	20320	24110	22625	9000	16310
point	10740	17340	24425	17080	13635	
Load at ultimate	19920	37250	28090	30220	16310	25470
	15990	24150	27375	25400	24050	24238
Elongation in	2.35	2.04	2.30	2.25	2.65	2.28
2 inches	2.34	2.14	2.30	2.23	2.28	2.30
Dimensions of red.	.375	.487	.355	.389	.369	.463
cross sec.	.339	.414	.368	.462	.444	.416
Area of cross	.2027	.1932	.1932	.1948	.2011	.2107
section	.1924	.1987	.1924	.1924	.2051	.2091
Area of reduced	.1104	.1863	.0990	.1188	.1069	.1684
cross sec.	.0903	.1346	.1064	.1676	.1548	.1359
Per cent reduction	45.1	22.2	48.7	39.0	46.8	20.1
of area	53.0	32.30	44.7	12.9	24.6	35.0
Per cent elongation	17.5		15	12.5	32.5	14.0
in 2 in.	17.0	7.0	15	11.5	14.0	15.0
Unit stress at	58300	77000	124700	116500	44800	77300
yield point	55800	87300	127000	88700	66500	
Unit stress at	98300	132800	145200	155000	81200	121000
ultimate	82900	121700	142000	132000	117200	116000
Character of	Half	C.&C.	Half	Ragged	Flat	Flat
fracture	C.&C.		C.&C.	But Flat		Radial
						Lines

REMARKS: D_7 Broke in grips.

D8 Broke just next to grips on prick punch mark.

F7 Broke in grips on prick punch mark.

TENSILE TEST

STEEL DRAWN AT 300°C

% Carbon	.52	.68	.80-.90	1.10-1.20
Mark or number	C9&10	D9&10	E9&10	F9&10
Dimensions of	.495	.497	.512	.516
cross section	.494	.497	.505	.513
Load at yield	21460	11115	12380	15710
point	16960	13680	11000	23600
Load at ultimate	33000	23150	15040	26740
	27575	27200	22290	36450
Elongation in	2.22	2.13	2.75	2.17
2 inches	2.22	2.14	2.20	2.29
Dimensions of	.383	.474	.326	.500
red.cross sec.	.425	.442	.463	.404
Area of cross	.1924	.1940	.2059	.2091
section	.1917	.1940	.2003	.2067
Area of reduced	.1152	.1765	.0835	.1963
cross sec.	.1419	.1534	.1684	.1282
Per cent reduction	40.1	9.02	59.0	6.12
of area	26.0	20.9	15.7	37.90
Per cent elongation	11	6.5	37.5	8.5
in 2 in.	11	7.0	10.0	14.5
Unit stress at	111500	57300	60100	75200
yield point	88300	70300	54800	114000
Unit stress at	171300	119200	73200	127800
ultimate	143800	140000	111000	176500
Character of	Half	Flat	Ragged	Flat
fracture	C.&C.			Ragged

REMARKS: C9 Broke near grips. Slipped in grips. Reading may be high.

D9 Broke on a prick punch mark.

TENSILE TEST

STEEL DRAWN AT 600°C

% Carbon	.14	.33	.52	.68	.80-.90	1.10-1.20
Mark or number	A11&12	B11&12	C11&12	D11&12	E11&12	F11&12
Dimensions of cross	.503	.499	.510	.493	.518	.519
section	.501	.503	.497	.499	.505	.512
Load at yield	6765	10355	11670	12580	8390	13800
point	7881	10165	11210	11180	9880	13575
Load at ultimate	10422	12875	15925	16540	15400	19050
	10560	13170	15815	17055	16390	18865
Elongation in	2.84	2.65	2.59	2.46	2.70	2.39
2 inches	2.78	2.68	2.54	2.35	2.56	2.36
Dimensions of	.277	.367	.359	.386	.398	.382
red. cross sec.	.379	.317	.318	.392	.331	.375
Area of cross	.1987	.1956	.2093	.1909	.2107	.2116
section	.1971	.1987	.1940	.1956	.2003	.2059
Area of reduced	.0603	.1058	.1012	.1170	.1244	.1146
cross sec.	.1128	.0789	.0794	.1207	.0861	.1104
Per cent reduction	69.7	45.9	50.3	38.7	40.9	45.8
of area	42.7	60.2	59.0	38.3	51.8	46.3
Per cent elongation	42	32.5	29.5	23	35.0	19.5
in 2 in.	39	34.0	27.0	17.5	28.0	18.0
Unit stress at	34000	52900	56900	65800	39800	65200
yield point	40000	51200	57700	57200	49300	65800
Unit stress at	52400	65700	77800	86700	73000	90000
ultimate	53500	66200	81500	87100	81600	91500
Character of	Half	Ragged	7/8	Ragged	Flat	Flat
fracture	C.&C.		C.&C.			

REMARKS: A_{11} Broke in grips.

B11 Broke on one of prick punch marks.

D_{11} Broke in grips. Prick punch mark caused weakening.

F_{12} Broke in grips.

D12 Broke on prick punch mark.

TENSILE TEST

STEEL HARDENED

% Carbon	.14	.33	.52	.68
Mark or number	A13&14	B13&14	C13&14	D13&14
Dimensions of	.500	.503	.499	.503
cross section	.508	.499	.503	.494
Load at yield	14810	16900	20780	
point	19850	15050	17750	
Load at ultimate	18200	35660	33980	
	21720	25990	31600	22380
Elongation in	2.15	2.00		
2 inches	2.27		2.12	2.00
Dimensions of	.449	.498	.485	
red. cross sec.	.389	.440	.476	.485
Area of cross	.1963	.1987	.1956	.1987
section	.2027	.1956	.1987	.1917
Area of reduced	.1583	.1948	.1847	
cross sec.	.1188	.1521	.1780	.1847
Per cent reduction	17.8	1.96	5.57	
of area	41.0	3.57	10.40	3.52
Per cent elonga-	7.5	0		
tion in 2 in.	13.5	2.0	6.0	0
Unit stress at	75400	85000	106000	
yield point	97900	105200	89300	
Unit stress at	92600	179500	173500	
ultimate	107000	192800	159000	116800
Character of	Very	Very	Flat	Flat
fracture	Ragged	Ragged		Rough

REMARKS: First A_{14} broke in grip 1" from end - no reading - pulled again and reading taken. Yield indistinct.

D_{14} Broke twice in grips.

A_{13} Broke in grips.

C_{14} " " "

D_{13} Too hard to hold in grips.

The yield on all these specimens is very uncertain.

TENSIL TEST

AVERAGE RESULTS

% Carbon	Treatment	A .14	B .33	C .52	D .68	E .80-.90	F 1.10-1.20
% Reduction of Area	1&2	65.3	56.9	43.0	28.1	47.3	52.5
"	3&4	55.3	55.8	59.6	27.6	28.0	38.8
"	5&6	49.0	27.3				
"	7&8			46.7	39.0	35.7	35.0
"	9&10			33.0	20.9	15.7	22.0
"	11&12	56.2	53.0	54.6	38.5	46.3	46.0
"	13&14	29.4	2.76	7.96	3.52		
% Elongation in 2 Inches	1&2	46.5	36.7	30.5	21.0	32.5	32.5
"	3&4	45.7	35.7	28	22.3	15.0	21.3
"	5&6	17.3	7.0				
"	7&8			15.0	12.0	14.0	14.5
"	9&10			11	6.8	10.0	16.5
"	11&12	40.5	33.3	28.3	20.3	31.5	18.7
"	13&14	10.5	1.0	6.0	0		
Unit Stress at Yield #/sq. in.	1&2	38,860	43400	53850	56750	41400	40450
"	3&4	27035	28700	43700	35600	70600	74000
"	5&6	57050	82150				
"	7&8			125850	104600	66500	77300
"	9&10			99900	63800	57450	75200
"	11&12	37000	52050	57300	61500	42550	65500
"	13&14	86650	95100	87650			
Unit Stress at Ultimate #/sq.in.	1&2	54825	69250	85550	108500	78400	75700
"	3&4	45650	53700	66700	80050	94700	93450
"	5&6	90600	127250				
"	7&8			143600	143500	117200	118500
"	9&10			157550	129600	111000	127800
"	11&12	52950	65950	79650	86900	77300	90750
"	13&14	99800	186150	166250	116800		

REPEATED STRESS DATA

% Carbon		.14		.33		.52	
		A		B		C	
		Initial	Final	Initial	Final	Initial	Final
		47563	48345	38728	39410	56267	56858
Normal	1	48350	48927	39410	40141	56858	57425
		34502	35225	61345	62067	73895	74247
"	2	35227	35806	62070	62815	74250	74630
		50324	51060	74634	75540	36932	37383
Annealed	3	51060	51855	75562	76488	37387	37774
		43507	44345	77710	78649	48928	49435
"	4	44345	45240	78650	79567	49441	49847
		65967	66490	60275	60673	-----	-----
Drawn at 200°C	5	66492	67040	-----	-----	-----	-----
		57426	57635	67043	67220	-----	-----
" " 200°C	6	57643	57803	67220	67515	-----	-----
		-----	-----	-----	-----	54623	54930
" " 300°C	9	-----	-----	-----	-----	54935	55270
		-----	-----	-----	-----	85016	85384
" " 300°C	10	-----	-----	-----	-----	85385	85760
		-----	-----	-----	-----	52952	53235
" " 400°C	7	-----	-----	-----	-----	53241	53610
		-----	-----	-----	-----	80240	80670
" " 400°C	8	-----	-----	-----	-----	80672	80986
		51858	52440	40923	41327	64231	64637
" " 600°C	11	52441	52950	41327	41735	64640	65057
		58378	58990	37810	38234	42644	43053
" " 600°C	12	58994	59695	38236	38725	43053	43505
Hardened	13	55862	56040	68810	69009	-----	-----
		56040	56264	69014	69085	-----	-----
		40142	40478	70682	71065	-----	-----
"	14	40479	40923	71068	71403	-----	-----

REMARKS: Specimens seem fine grained near point of break.

C_9 Broke suddenly.

B_5 Broke 1" from chuck.

REPEATED STRESS DATA

% Carbon		.68		.80-.90		1.10-1.20	
		D		E		F	
		Initial	Final	Initial	Final	Initial	Final
		33490	33990	72007	72608	80987	81427
Normal	1	33996	34500	72610	73237	81428	81907
		76490	77052	35815	36351	45243	45644
"	2	77055	77710	36354	36930	45645	46012
		79568	80129	62821	63114	57804	58134
Annealed	3	———	———	63121	63460	58134	58375
		———	———	73238	73580	46012	46360
"	4	68157	68645	73581	73890	46365	46829
				83310	83735	60674	60880
Drawn at 300°C	9	Broken		83741	84115	60883	61343
		67522	67775	65059	65444	63463	63798
" " 300°C	10	67780	68090	65448	65963	63799	64225
		Broken		69086	69570	41746	42284
" " 400°C	7			69581	69825	42285	42625
		85761	86105	46830	47209	69830	70165
" " 400°C	8	86105	86415	47211	47560	70168	70680
		49849	50022	84119	84550	55276	55535
" " 600°C	11	50022	50323	84550	85016	55538	55820
		53613	53925	82478	82870	71407	71745
" " 600°C	12	53927	59213	82870	83307	71745	72005

REMARKS: F_9 broke well above chuck.

F_2 " 1/4 " " "

D_{11} Apparent hardening strains caused longitudinal cracks (only one end)

D_{12} " " " " " " (both ends)

D_{10} " " " " " " (one end)

D_4 " " " " " " (one end)

D_3 " " " " " " (one end)

REPEATED STRESS TESTS

CYCLES TO RUPTURE & CHARACTER OF FRACTURE

% Carbon	A .14 Cycles Read	Ave Cycles	Fracture (Figures give distance of ridge from center)	B .33 Cycles Read	Ave Cycles	Fracture (Figures give distance of ridge from center)
	782		1/32 ragged fine and	682		1/32 Uneven and
Normal	577		1/16 granular	731		1/16 fine
	723		1/16 ragged and	722		1/16 ragged
"	579	665	1/16 coarse	745	720	3/32 fine
	736		1/16 even &	906		1/16 square
Annealed	795		1/32 fine grain	926		1/16 fine
"	838		1/32 cupped	939		1/16 ragged
	895	816	0 fine structure	917	922	1/16 fine
	523		0 ragged &	398		1/8 square
Drawn at 200°C	548		1/8 fine			fine
	209		Edge flat &	177		square
" " 200°C	160	360	1/32 coarse	295	290	granular
	582		0 even &	404		1/32
" " 600°C	509		1/32 fine	408		1/32 fine
	612		1/32 ragged &	424		1/32 ragged
" " 600°C	681	596	0 fine	489	431	0 coarse
	178			199		square
Hardened	224		edge coarse	91		coarse
	336		3/64 ragged &	383		square
"	444	295	1/64 fine	335	252	fine grain

REPEATED STRESS TESTS

CYCLES TO RUPTURE & CHARACTER OF FRACTURE

% Carbon	C			D		
	.52			.68		
	Cycles Read	Ave Cycles	Fracture (Figures give distance of ridge from center)	Cycles Read	Ave Cycles	Fracture (Figures give distance of ridge from center)
	591		1/16 ragged	500		3/32 smooth
Normal	567		1/16 fine	504		1/8 fine grain
	352		0 fine	562		edge ragged
"	380	475	1/8 granular	655	555	fine
	451		1/16 rough	561		edge ragged
Annealed	387		0 fine			granular
	507		1/8 Square			square
"	406	439	1/8 granular	488	528	coarse
	307		1/16 one edge low			
Drawn at 300°C	335		1/16 fine			
	368		edge coarse &	253		1/8 ragged
" " 300°C	375	362	granular	310	281	granular
	283		0 ragged			
" " 400°C	369		0 fine			
	430		1/16 ragged	334		1/8 ragged
" " 400°C	314	365	0 fine	310	322	fine
	406		1/32 ragged			0 ragged
" " 600°C	417		0 fine	301		0 fine
	409		1/32 regular	312		3/32 ragged
" " 600°C	452	421	1/32 fine	286	299	fine

REPEATED STRESS TESTS

CYCLES TO RUPTURE & CHARACTER OF FRACTURE

% Carbon	E .80-.90 Cycles Read	Ave Cycles	Fracture (Figures give distance of ridge from center)	F 1.10-1.20 Cycles Read	Ave Cycles	Fracture (Figures give distance of ridge from center)
	601		1/16 ragged	440		square ragged
Normal	627		fine	479		fine
	436		5/32 ragged	401		edge ragged
"	576	560	edge fine	367	422	fine
	293		edge flat	330		edge ragged
Annealed	339		fine	241		fine grain
	342		edge ragged	348		1/32 uneaven
"	309	321	coarse	464	346	center fine
	425		near square fine	206		3/32 square
Drawn at 300°C	374		edge granular	460		1/8 fine
	385		3/32 square fine	335		1/8 ragged
" " 300°C	515	425	granular	426	357	1/8 fine
	484		square, fine	538		1/32 very fine
" " 400°C	244		& granular	340		1/32 very fine
	379		edge fine on outside	335		1/8 square
" " 400°C	349	364	coarse in	412	406	fine grain
	431		1/16 convex	259		0 one end flat
" " 600°C	466		very fine	282		other ragged fine grain
	392		1/8 ragged	338		square
" " 600°C	437	431	fine	260	285	ragged fine

DATA FOR IMPACT TESTS

% Carbon		A .14		B .33		C .52		Breaks A	Breaks B	Breaks C
Normal	1	------	------	28°9'	4°41'	28°14'	16°35'			
"	2	39°17'	14°15'			28°19'	16°27'			Very fine Grainy
Annealed	3	32°14'	14°35'	28°13'	18°24'	28°13'	21°45'	Amorphous with Crys.		
"	4	------	------	28°7'	20°44'	28°15'	7°52'		Crys.	
Drawn at 200°C	5	------	------	28°18'	26°44'	------	------		Fine small Crys.	
Drawn at 200°C	6	32°21'	26°44'	28°13'	23°24'	------	------		Very fine	Very fine silky
Drawn at 400°C	9	------	------	------	------	28°8'	18°3'			fine grains
Drawn at 400°C	10	------	------	------	------	28°19'	18°37'			fine granular
Drawn at 300°C	7	------	------	------	------	28°8'	27°8'			gray almost amorphous
Drawn at 300°C	8	------	------	------	------	28°13'	27°5'	Crys. growth		
Drawn at 600°C	11	32°11'	15°43'	32°10'	19°55'	28°19'	6°9'			
Drawn at 600°C	12	------	------	------	------	28°15'	16°19'			
Hardened	13	32°9'	28°8'	28°11'	26°46'	28°6'	27°14'	fine amorphous	very fine	very fine amorphous
"	14	32°20'	25°7'					"		

For Friction Correction	θ_1 Initial	θ_2 Final	$\frac{\theta_1-\theta_2}{\theta_1+\theta_2}$	θ_1 Initial	θ_2 Final	$\frac{\theta_1-\theta_2}{\theta_1+\theta_2}$
	19°40'	19°29'	.281	28°7'	27°57'	.1733
	20°20'	19°30'	1.255	32°11'	31°54'	.265
	20°15'	19°39'	.920	39°12'	38°51'	.268
		Ave	.819			

REMARKS: A_4 did not break.

B_{12} " " "

A_{12} " " "

A_1 " " "

DATA FOR IMPACT TESTS

		D		E		F		Breaks		
% Carbon		.68		.80-.90		1.10-1.20				
Normal	1	28°7'	26°47'	28°18'	26°49'	28°18'	27°18'	fine grains	granular	fine
"	2	28°12'	26°49'	28°15'	25°56'	28°10'	26°56'	gran-ular		
Annealed	3	28°11'	26°48'	19°7'	17°9'	28°14'	27°9'	coarse	coarse grains	very very fine
"	4	28°17'	26°42'	28°8'	26°57'	28°12'	27°8'	gran-ular	" "	fairly fine grains
Drawn at 300°C	9			28°8'	25°1'	28°10'	27°10'		fine grains	fine
Drawn at 300°C	10			28°16'	24°57'	28°16'	27°16'		fine	fine gran-ular
Drawn at 400°C	7	28°11'	23°13'	28°13'	26°25'	28°13'	27°8'	very very fine	fine silky	grainy
Drawn at 400°C	8	28°9'	23°46'			28°7'	27°5'	fine & granu-lar		fine struct-ure
Drawn at 600°C	11	28°14'	10°35'	28°14'	25°52'	28°12'	27°3'		fine grains	
Drawn at 600°C	12	28°16'	20°31'	28°11'	24°40'	28°10'	26°38'		fine crys.	fine silky

REMARKS: D_7 Showed cracks due to hardening strains.

IMPACT TESTS

CORRECTED ANGLES AND ENERGY OF RUPTURE

% Carbon	A .14 Initial	A .14 Final	A .14 Energy of Rupture	B .33 Initial	B .33 Final	B .33 Energy of Rupture
Normal	----------	----------	----------	$28^{0}4'$	$4^{0}42'$	506
"	$39^{0}7'$	$14^{0}19'$	859	----------	----------	----------
" Average			859			506
Annealed	$32^{0}6'$	$14^{0}39'$	540	$28^{0}8'$	$18^{0}27'$	295
"	----------	----------	----------	$28^{0}2'$	$20^{0}48'$	225
" Average			540			260
Drawn at $200^{0}C$	----------	----------	----------	$28^{0}13'$	$26^{0}49'$	56
" " $200^{0}C$	$32^{0}13'$	$26^{0}51'$	200	$28^{0}8'$	$23^{0}28'$	155
" " $200^{0}C$ Ave			200			105
" " $600^{0}C$	$32^{0}3'$	$15^{0}47'$	511	$32^{0}2'$	20^{0}	310
" " $600^{0}C$	----------	----------	----------	----------	----------	----------
" " $600^{0}C$ Ave			511			310
Hardened	$32^{0}1'$	$28^{0}15'$	150	$28^{0}6'$	$26^{0}51'$	52
"	$32^{0}12'$	$25^{0}14'$	257	----------	----------	----------
" Ave			203			52

IMPACT TESTS

CORRECTED ANGLES AND ENERGY OF RUPTURE

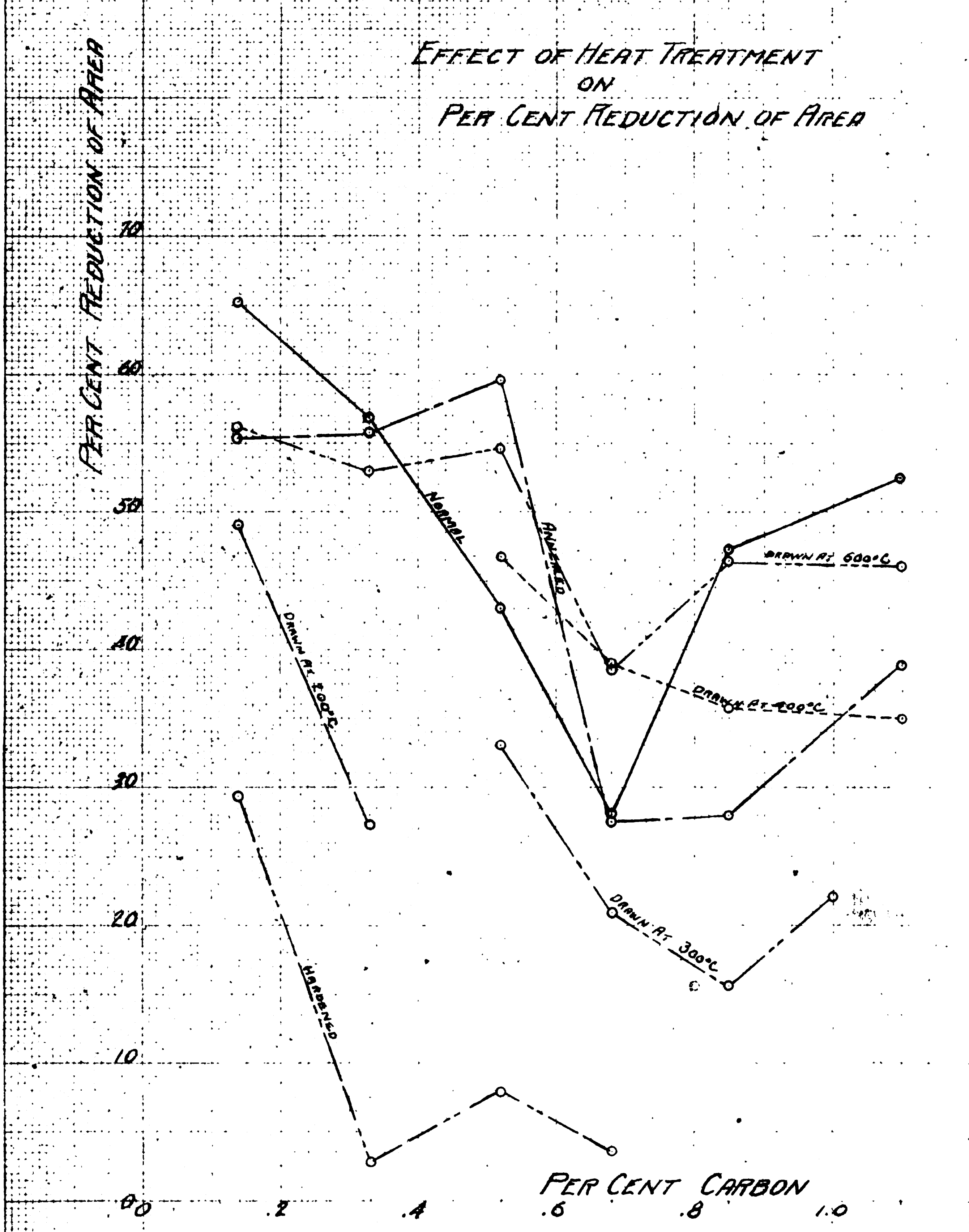
% Carbon	C .52 Initial	Final	Energy of Rupture	D .68 Initial	Final	Energy of Rupture
Normal	28°9'	16°38'	340	28°2'	26°52'	39
"	28°14'	16°30'	343	28°7'	26°54'	40
" Ave			341			39
Annealed	28°8'	21°49'	200	28°6'	26°53'	39
"	28°10'	7°55'		28°12'	26°47'	45
" Ave			200			42
Drawn at 300°C	28°3'	27°11'	30			
" " 300°C	28°8'	27°8'	32			
" " 300°C Ave			31			
" " 400°C	28°3'	18°6'	301	28°6'	23°17'	154
" " 400°C	28°14'	18°40'	302	28°4'	23°50'	142
" " 400°CAve			301			148
" " 600°C	28°14'	6°10'		28°9'	10°37'	
" " 600°C	28°10'	16°22'	353	28°11'	20°34'	242
" " 600°CAve			353			
Hardened	28°1'	27°17'	22			
"						
" Ave			22			

IMPACT TESTS

CORRECTED ANGLES AND ENERGY OF RUPTURE

% Carbon	E .80-.90 Initial	E .80-.90 Final	E .80-.90 Energy of Rupture	F 1.10-1.20 Initial	F 1.10-1.20 Final	F 1.10-1.20 Energy of Rupture
Normal	28°13'	26°54'	72	28°13'	27°23'	25
"	28°10'	26°1'	40	28°5'	27°1'	34
" Ave			50			30
Annealed	18°51'	15°55'	67	28°9'	27°14'	32
"	28°3'	27°2'	32	28°7'	27°13'	32
" Ave			52			32
Drawn at 300°C	28°3'	25°5'	107	28°5'	27°15'	27
" " 300°C	28°11'	25°1'	110	28°11'	27°21'	25
" " 300°C Ave			108			26
" " 400°C	28°8'	26°30'	52	28°8'	27°13'	32
" " 400°C				28°2'	27°10'	30
" " 400°C Ave			52			31
" " 600°C	28°9'	25°57'	122	28°7'	27°8'	34
" " 600°C	28°6'	24°44'	72	28°5'	26°43'	44
" " 600°C Ave			97			39

PLATE I


EFFECT OF HEAT TREATMENT
ON
PER CENT REDUCTION OF AREA
PER CENT REDUCTION OF AREA
70
60
50
40
30
20
10
0
NORMAL
ANNEALED
DRAWN AT 600°C
DRAWN AT 400°C
DRAWN AT 300°C
DRAWN AT 200°C
HARDENED
PER CENT CARBON
0
.2
.4
.6
.8
1.0

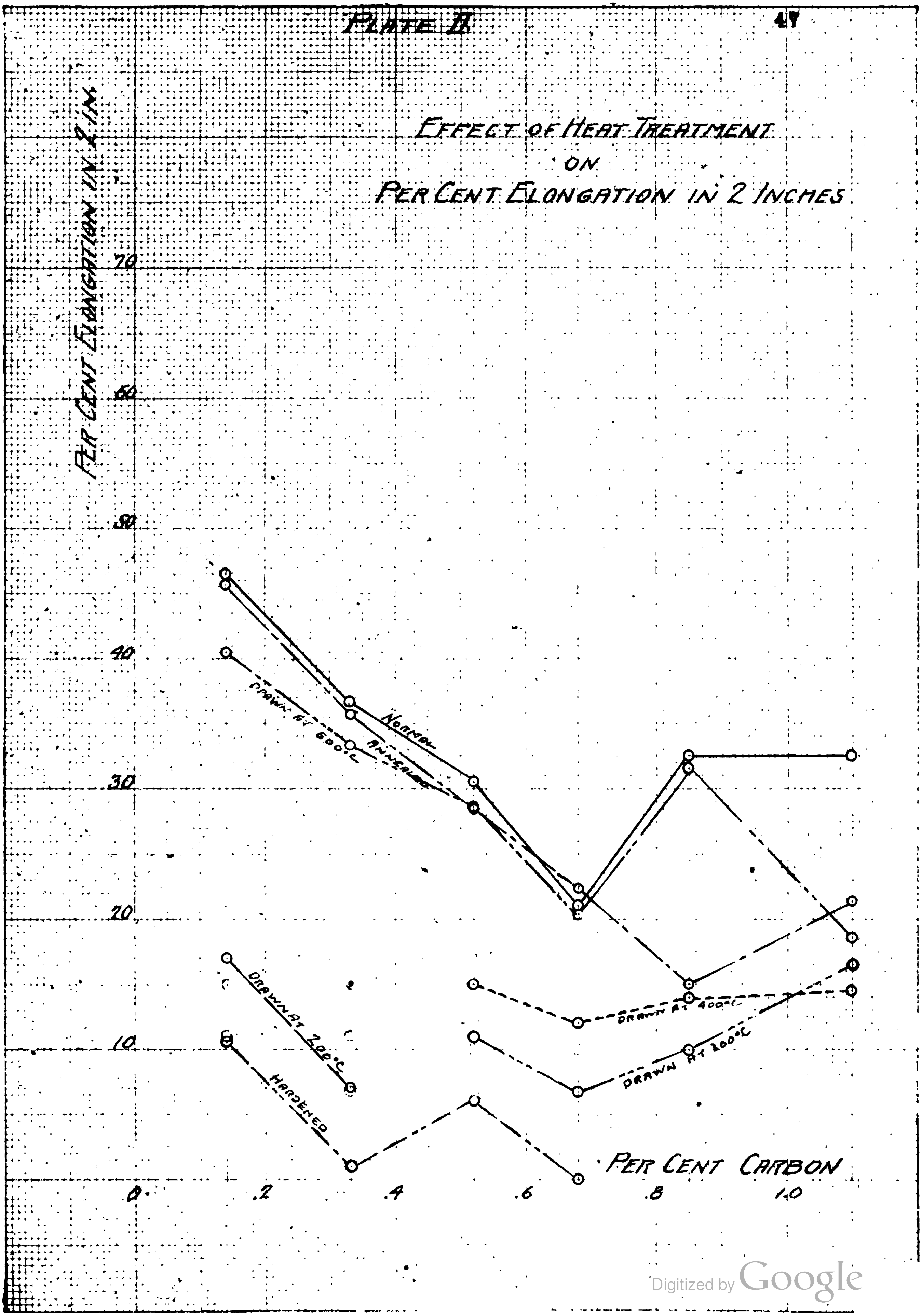


PLATE II
47
EFFECT OF HEAT TREATMENT
ON
PER CENT ELONGATION IN 2 INCHES
PER CENT ELONGATION IN 2 IN.
70
60
50
40
30
20
10
NORMAL
ANNEALED
DRAWN AT 600°C
DRAWN AT 400°C
DRAWN AT 300°C
DRAWN AT 200°C
HARDENED
PER CENT CARBON
0
.2
.4
.6
.8
1.0

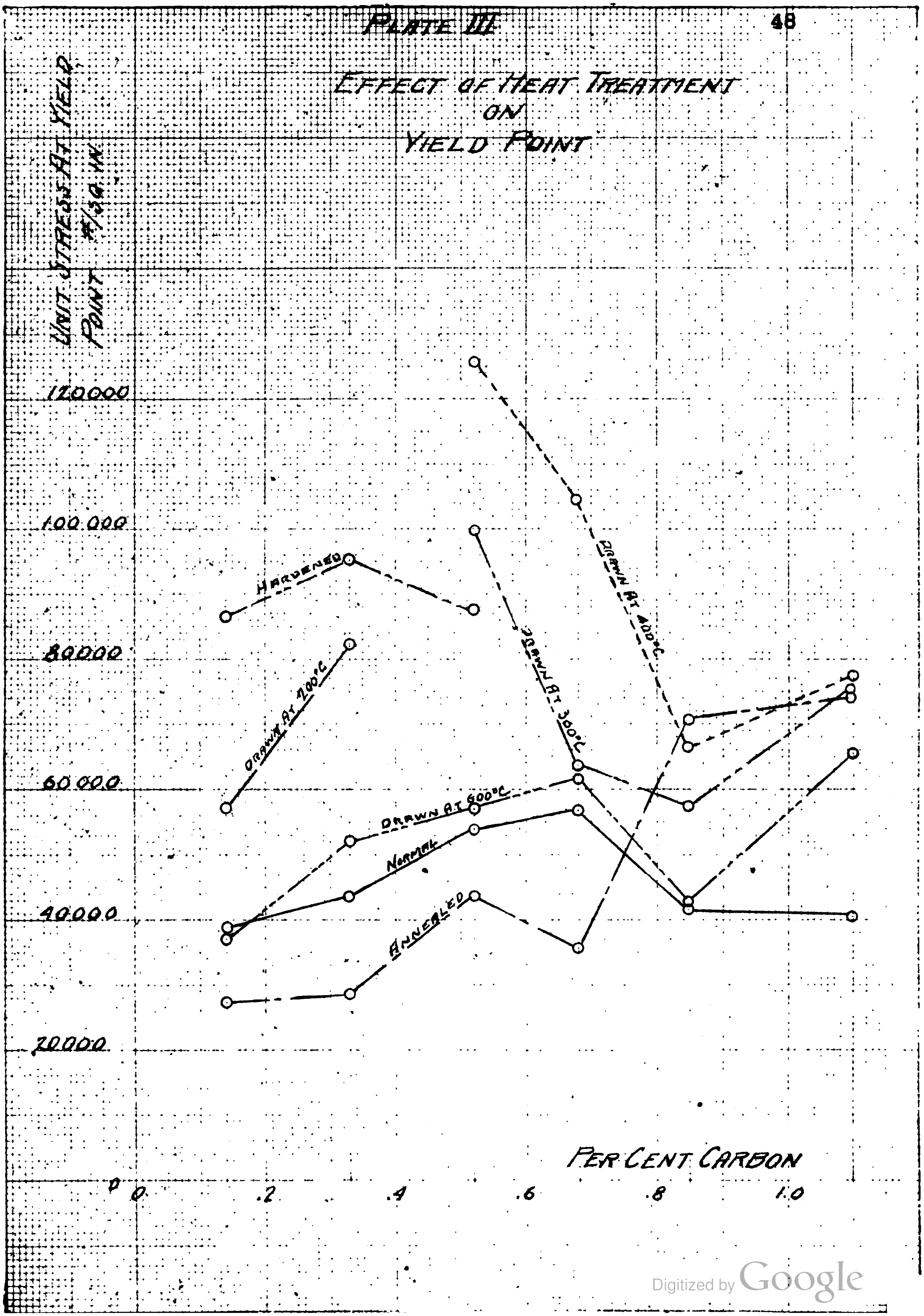


PLATE III
EFFECT OF HEAT TREATMENT
ON
YIELD POINT
UNIT STRESS AT YIELD POINT #/SQ IN.
120000
100000
80000
60000
40000
20000
HARDENED
DRAWN AT 200°C
DRAWN AT 300°C
DRAWN AT 400°C
DRAWN AT 600°C
NORMAL
ANNEALED
PER CENT CARBON
0
.2
.4
.6
.8
1.0

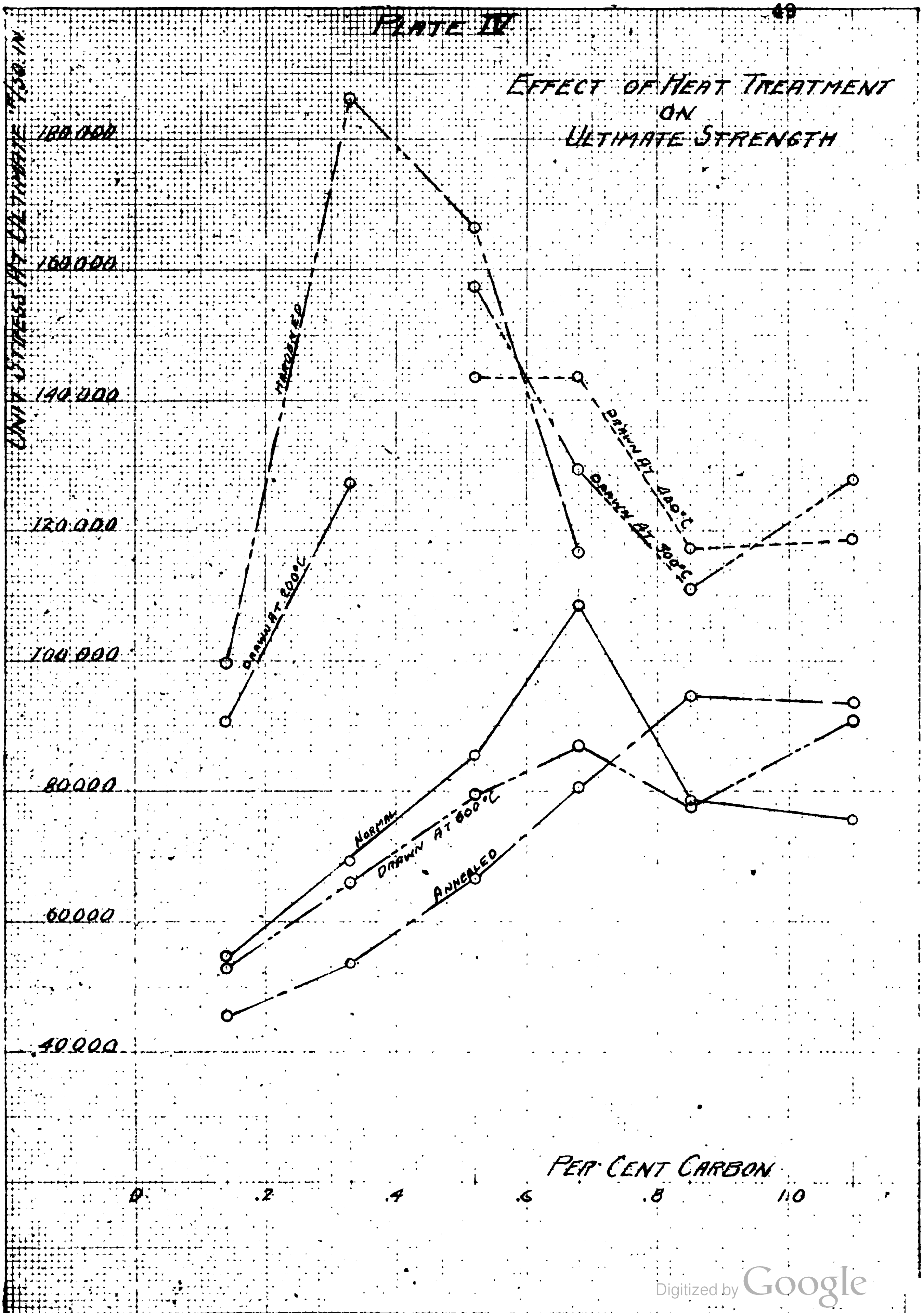


PLATE IV
EFFECT OF HEAT TREATMENT ON ULTIMATE STRENGTH
UNIT STRESS AT ULTIMATE #/SQ IN
180000
160000
140000
120000
100000
80000
60000
40000
PER CENT CARBON
0
.2
.4
.6
.8
1.0
HARDENED
DRAWN AT 600°C
DRAWN AT 400°C
NORMAL
ANNEALED

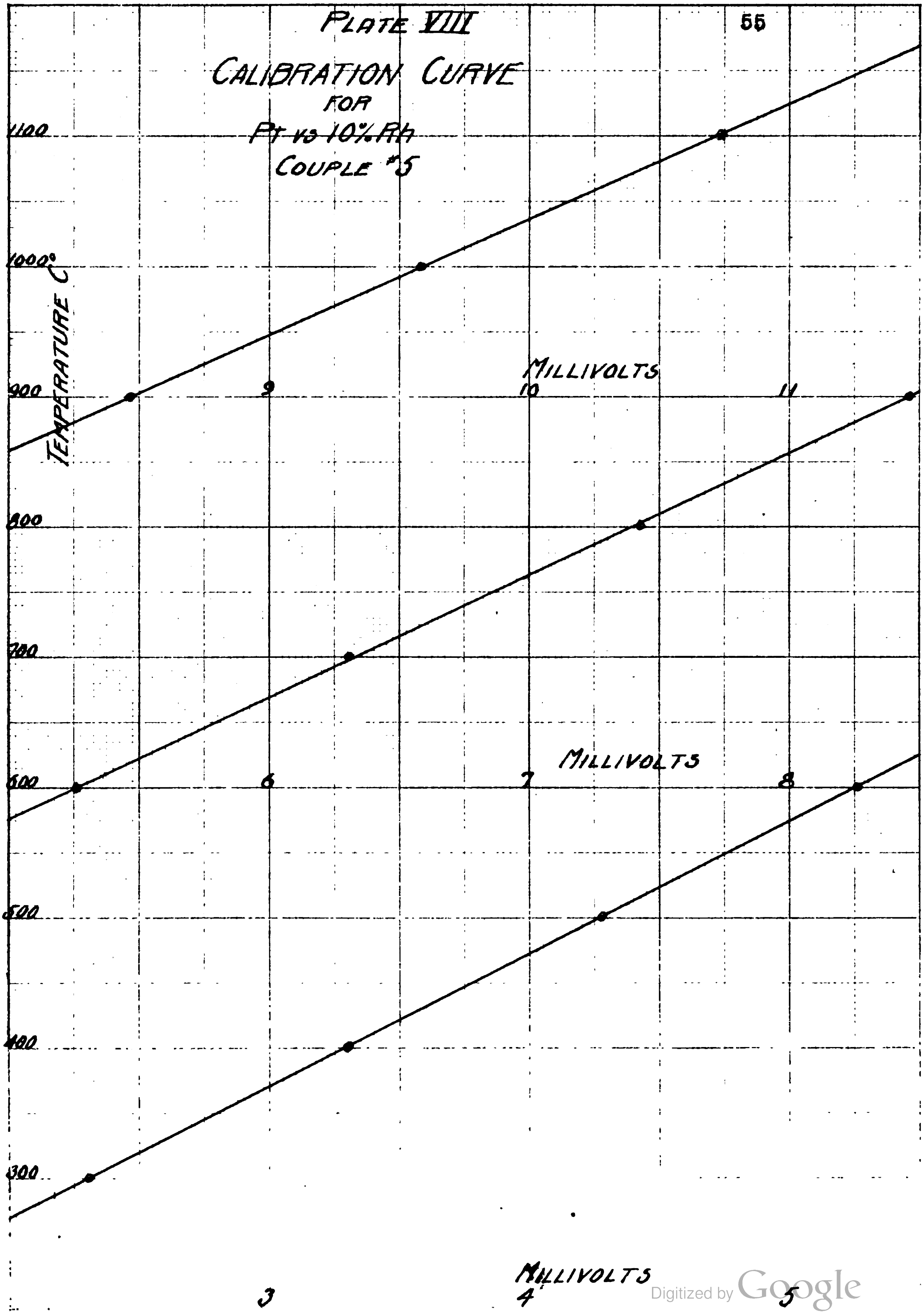
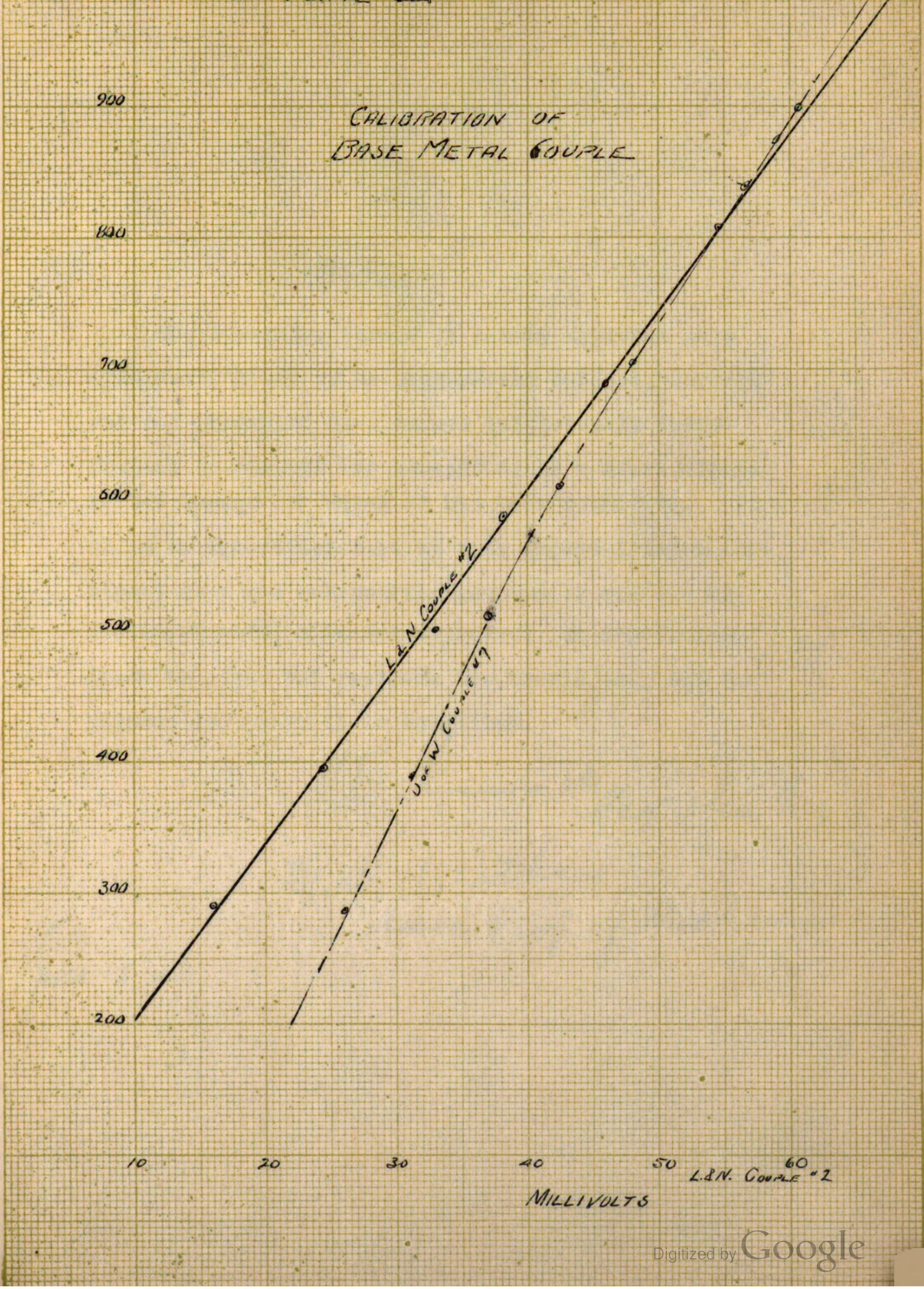


PLATE VIII
CALIBRATION CURVE
FOR
PT VS 10% RH
COUPLE #5
TEMPERATURE C
1100
1000°
900
800
700
600
500
400
300
MILLIVOLTS
9
10
11
MILLIVOLTS
6
7
8
MILLIVOLTS
3
4
5

PLATE IX


CALIBRATION OF
BASE METAL COUPLE
L & N COUPLE #2
U of W COUPLE #7
900
800
700
600
500
400
300
200
10
20
30
40
50
60
L.&N. COUPLE #2
MILLIVOLTS

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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June 13, 1918.